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13. ABSTRACT *(Maximum 200 words)*

The full effects of the problem of control surface freeplay in an aeroelastic system are examined in the context of a three degree-of-freedom aeroelastic typical section. A computationally efficient numerical model of the nonlinear system is presented, in which the control surface freeplay is modeled as a system of piecewise linear state-space models. The system response is determined by time marching of the governing equations using a standard Runge-Kutta algorithm in conjunction with Henon's method for integrating a system of equations to a prescribed surface of phase space section. An experimental model which closely approximates the three degree-of-freedom typical section in two-dimensional, incompressible flow has been created to validate the theoretical model. Consideration is also given to modeling realistically the structural damping present in the experimental system. Limit cycle oscillations are studied numerically and experimentally. The numerical model captures the full range of nonlinear behavior present in the physical system, including decaying oscillations, limit cycles, quasiperiodicity, nonperiodicity, possible chaos and divergent flutter. Nonlinear stability analyses are also performed providing insight into the types of bifurcations which occur as the freestream conditions changes and allowing for the prediction of such bifurcations in the experimental model.

Some preliminary results are also presented for the control of undesirable behavior together with suggestions for further research.

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9-9-96

Final Report on the AASERT award

Control of Nonlinear Behavior - Experiments

(AFOSR grant F49620-93-1-0382)

Prof. L.N. Virgin, Principal Investigator
Prof. E.H. Dowell, co-Principal Investigator

Participants:
Mark D. Conner, graduate student, full support
AASERT award recipient

Chris Begley, graduate student, partial support

Department of Mechanical Engineering and Materials Science
Duke University, Durham, NC 27708-0300.

Dr. Brian Sanders,
Program Manager, AFOSR

2. Objectives

The objectives of this research were to conduct a thorough analysis of a nonlinear aeroelastic system with emphasis on theoretical-experimental model correlation and an initial study into various control strategies.

3. Status of effort

The research achieved the stated objectives. Both mathematical and experimental models gave impressive results, and excellent agreement has been achieved. This work is summarized in the publications listed below. The research expertise built-up over this period will provide a strong foundation for the next phase of the research program.

4. Accomplishments/New Findings

The successful correlation between theory and experiment has resulted in the production of at least four journal papers (see below). As mentioned above, the data from the various control strategies (which aim to increase the flutter speed of this kind of typical section) is currently being analyzed. Initial results from the control study have also appeared in the literature and are also contained in the list of references.

5. Personnel Supported

This AASERT award provides support for Mark Conner, a graduate student in the department of Mechanical Engineering and Materials Science. The research formed the basis for his PhD dissertation which was completed during the summer (see title and abstract attached). A small amount of support was provided for another graduate student - Chris Begley, who assisted with some of the experimental details and conducted a review of the role of Coulomb damping in experiments. This is an aspect of the modeling that will receive further consideration in future directions of this research.

6. Publications

The following publications which are in various stages of completion are:

M.D. Conner, D.M. Tang, E.H. Dowell and L.N. Virgin (1997) 'Nonlinear behavior of a typical airfoil section with control surface freeplay,' *6th Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures*, Blacksburg VA.

M.D. Conner, D.M. Tang, E.H. Dowell and L.N. Virgin (1997) 'Nonlinear aeroelasticity of an airfoil with control surface freeplay,' *35th Aerospace Sciences Meeting and Exhibit*, Reno, paper # AIAA 97-0579.

M.D. Conner, L.N. Virgin and E.H. Dowell (1996) 'Accurate numerical integration of state-space models for aeroelastic systems with freeplay,' *AIAA Journal*, **34**, pp. 2202-2205.

M.D. Conner, D.M. Tang, E.H. Dowell and L.N. Virgin (1997) 'Nonlinear behavior of a typical airfoil section with control surface freeplay,' *Journal of Fluids and Structures*, **11**.

L.N. Virgin, E.H. Dowell and M.D. Conner (1997) 'An airfoil with freeplay nonlinearity - complex limit cycle behavior,' in preparation.

J.S. Vipperman, R. L. Clark, Mark D. Conner, Earl H. Dowell, 'Investigation of the experimental active control of a typical section airfoil using a trailing edge flap,' submitted for publication to *Journal of Aircraft*.

J.S. Vipperman and R. L. Clark, 'Investigation of the experimental active control of a typical section airfoil with a trailing edge flap,' submitted for the *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, FL, 1997.

A number of informal seminars and workshops were also attended where aspects of this material were presented.

7. Interactions/Transitions

A number of presentations have been made connected with the parent award. Associated with this AASERT award Mark Conner attended a major nonlinear vibrations conference and presented a paper. Aspects of this research and their relation to the parent grant have also been discussed at various other conferences and workshops. Representatives of the AFOSR have also visited Duke University.

8. New discoveries, inventions, or patent disclosures

Initial indications are that the flutter speed of this type of airfoil can be significantly increased based on numerical simulations. Specifically the finite jump in amplitude is a new feature which is found consistently in both simulations and experiment. A number of other abrupt transitions occur and may have serious consequences since they are found for flow speeds considerably below the nominal linear flutter boundary. These are thoroughly nonlinear phenomena. The scaling of the response with freeplay magnitude is confirmed. This has implications for wear and maintenance programs. No patents.

9. Honors/Awards

One of the PI's (E.H. Dowell) was elected to the National Academy of Engineering during the tenure of this award. The other (L.N. Virgin) was promoted and received tenure. A PhD (Mark Conner) was completed and successfully defended (see appendix).

Appendix:

Abstract of the PhD Dissertation of Mark Conner, the graduate student supported by this AASERT award.

NONLINEAR AEROELASTICITY OF AN AIRFOIL SECTION WITH CONTROL SURFACE FREEPLAY

by

Mark D. Conner

Department of Mechanical Engineering and Materials Science
Duke University

Date: 6/21/96

Approved:

L. Virgin

Dr. Lawrence N. Virgin, Supervisor

Earl Dowell

Dr. Earl H. Dowell

Rob Clark

Dr. Robert L. Clark

Josiah Knight

Dr. Josiah D. Knight

Tod A. Laursen

Dr. Tod A. Laursen

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Mechanical Engineering and Materials Science in the Graduate School of Duke University

1996

Abstract

The full effects of the problem of control surface freeplay in an aeroelastic system are examined in the context of a three degree-of-freedom aeroelastic typical section. A computationally efficient numerical model of the nonlinear system is presented, in which the control surface freeplay is modeled as a system of piecewise linear state-space models. The system response is determined by time marching of the governing equations using a standard Runge-Kutta algorithm in conjunction with Henon's method for integrating a system of equations to a prescribed surface of phase space section. An experimental model which closely approximates the three degree-of-freedom typical section in two-dimensional, incompressible flow has been created to validate the theoretical model. Consideration is also given to modeling realistically the structural damping present in the experimental system. Limit cycle oscillations are studied numerically and experimentally. The numerical model captures the full range of nonlinear behavior present in the physical system, including decaying oscillations, limit cycles, quasiperiodicity, nonperiodicity, possible chaos and divergent flutter. Nonlinear stability analyses are also performed providing insight into the types of bifurcations which occur as the freestream conditions change and allowing for the prediction of such bifurcations in the experimental model.

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